Fabrication of binary phase surface relief optical elements by selective deposition of dielectric layers

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We propose and demonstrate a new scheme to fabricate surface relief binary phase elements by using selective deposition of dielectric layers through a contact mask. By using *in situ* optical thickness monitoring, accurate (~1%), repeatable, and robust layer thicknesses are readily obtained, leading to accurate phases. We demonstrate our scheme by forming a circular π phase element that is used to form a dark optical trap for atoms. © *1999 American Institute of Physics.* [S0034-6748(99)04702-4]

I. INTRODUCTION

Surface relief phase optical elements can perform complicated optical operations with high efficiency, durability, and robustness. The surface relief is usually formed by removal of material from an initially flat surface by either mechanical means or by etching.[1] Indeed, diffraction efficiencies of diffractive elements that have properly graded surface relief can approach 100%.[2] However in order to obtain such efficiencies it is necessary to resort to complex fabrication processes that can provide the needed accuracy for controlling the graded shape and the surface grooves. For example, to obtain 99% efficiency in a blazed surface relief grating, 5% accuracy in the groove depth is required.[3]

In general, it is difficult to control the proper etch depth accurately, because the rate of etching depends on many parameters such as temperature, etch concentration, aging, and oxidation effects.[4] A possible solution that may eliminate the need for accurate etch depth is to rely on deposition technology in which the depth of the surface groves is controlled by deposition of layers rather than by etching. With deposition it is possible to achieve extremely accurate groove depth; for example, accuracy approaching one atomic layer was demonstrated.[5] Using such an approach we demonstrated hetrostructure multilevel binary elements that relied on metal deposition technology and selective etching to obtain accurate depth.[4]

In this article we extend the deposition approach in two main respects: we use deposition of dielectric materials rather than metals, and we deposit the material selectively by evaporation through a contact mask. These extensions yield several important benefits. First, by adapting the dielectric materials to the required wavelength range of the element, it can operate as a transmission element as well as a reflection element (using metallic coatings). Second, no etching is required in this process, and third, *in situ* optical monitoring of the deposited layer thickness can be applied so the deposition process could be stopped at exactly the required depth. This approach is used extensively for (uniform) optical coatings, eliminates the necessity for precise control over all the process parameters, and is therefore extremely robust.

II. FABRICATION PROCESS

Our fabrication process is described with the aid of Fig. 1. It is based on a commercial dielectric evaporator.[6] The material is evaporated in high vacuum ($\sim 10^{-6}$ Torr) using a scanning electron beam. The deposition rate is fixed and kept constant (at 0.2–0.5 nm/s) by a piezoelectric transducer (PZT)-based deposition monitor and feedback on the electron beam current. An *in situ* monochromator and a photomultiplier tube measure the reflectivity of a specific wavelength (with 1 nm accuracy) from the substrate, and enable the evaporation to be stopped (manually) at the required layer thickness. Lamp modulation and lock-in detection of the optical reflection eliminate noise and dc offsets caused by stray light.

Our layer thickness procedure is demonstrated with the following example: deposition of a transmission π phase layer for $\lambda_{\text{laser}} = 514.5\,\text{nm}$ by evaporation of MgF_2 ($n_{\lambda_{\text{laser}}} = 1.38$; measured with an ellipsometer) on a BK7 glass substrate ($n = 1.52$). The desired layer thickness is therefore

$$d = \lambda_{\text{laser}}/2(n_{\lambda_{\text{laser}}} - 1) = 677 \text{ nm}. \quad (1)$$

The reflectance at the selected monochromator wavelength λ_{mono} is a sinusoidal function of d with a ''half period'' given by

$$2 n_{\lambda_{\text{mono}}} d \cos \alpha = M \lambda_{\text{mono}}/2, \quad (2)$$

where $\alpha = 15°$ is half the reflection angle of the monochromator beam, and M is the number of ''half periods.'' A typical plot of the reflection as a function of evaporation time is shown in Fig. 2, where the evaporation is stopped after $M = 4$ half periods. As seen, the reflectivity changes in approximately a sinusoidal manner with time indicating a relatively constant deposition rate, as expected. We found that the most reproducible layer thickness is obtained when the evaporation is stopped after an odd integer number (M) of half periods in the reflection plot.[7] Combining Eqs. (1) and (2) we get

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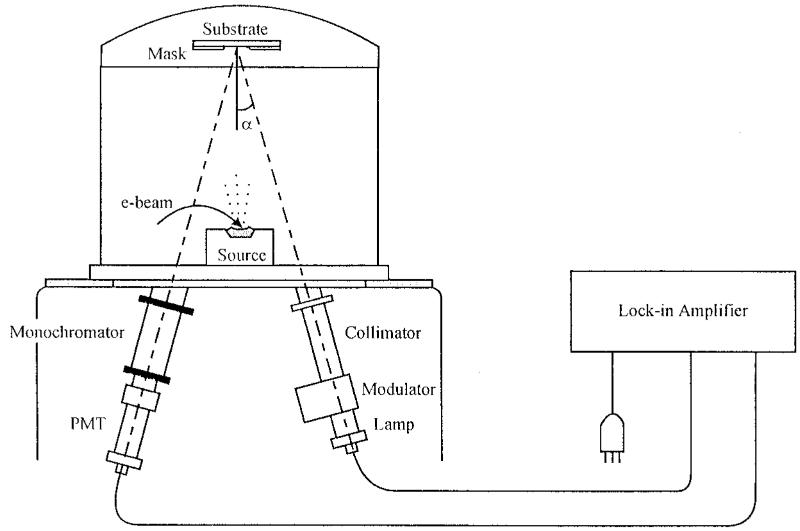

FIG. 1. Experimental setup for a binary surface relief phase element by evaporation of dielectric layers through a space-variant metallic contact mask. The modulated lamp, the monochromator, the photomultiplier tube (PMT) and the lock in amplifier compose the *in situ* optical monitoring equipment. Not shown are the vacuum chamber ($\sim 10^{-6}$ Torr) and the PZT-based evaporation rate monitor.

$$\frac{\lambda_{\text{mono}}}{\lambda_{\text{laser}}}=\frac{1}{M}\,\frac{2n_{\lambda_{\text{mono}}}\cos\alpha}{n_{\lambda_{\text{laser}}}-1}, \tag{3}$$

where the layer index of refraction may be wavelength dependent. Equations (1)–(3) are also applicable for surface relief phase elements in the reflection mode (formed by coating the element with a reflective layer) by using $n_{\lambda_{\text{mono}}} = -1$. For our transmission element with $\alpha = 15°$, $\lambda_{\text{laser}} = 514.5\,\text{nm}$, $n_{\lambda_{\text{laser}}} = n_{\lambda_{\text{mono}}} = 1.38$ and choosing $M = 7$, Eq. (3) yields $\lambda_{\text{mono}} = 516\,\text{nm}$. Note that the choice of $M \gg 1$ decreases the error of the layer thickness that results from stopping the evaporation not exactly at the fringe bottom by a factor of M, as compared to $M = 1$. We found that using large values of M indeed improved the accuracy of the evaporated layer thickness.

For phase elements smaller then a few centimeters the best results were obtained where the optical thickness monitoring is performed in the close vicinity of the element. Otherwise (e.g., when many elements are fabricated simultaneously) a calibration factor should be used in Eq. (3), as is done routinely in evaporation machines. We found that such a calibration factor is reproducible to better then 1% over a period of several months.

To form space variant surface profiles we used selective evaporation through a contact mask. We considered three

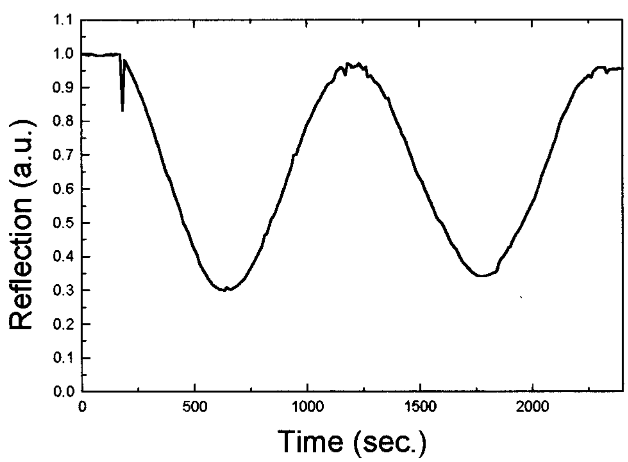

FIG. 2. The reflectance at the selected monochromator wavelength λ_{mono} as a function of evaporation time. Since $n_{\text{layer}} < n_{\text{substrate}}$ the reflection initially decreases. The sharp spike at $T = 200$ s is an electronic artifact that occurs at the beginning of evaporation.

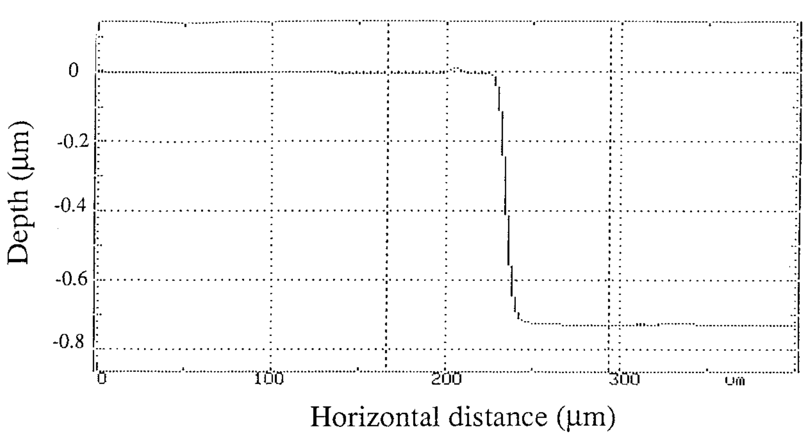

FIG. 3. A surface profilometer trace for a typical edge of the evaporated area. The ~10 μm slope is due to the limited resolution of the profilometer.

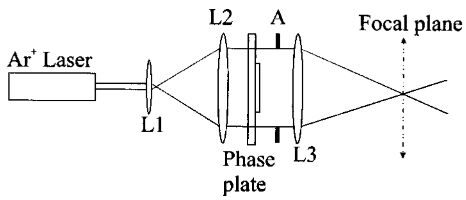

FIG. 4. Experimental setup for optical characterization of a dark focal region formed with a π phase mask. $L1$ and $L2$ lenses compose a telescope that expends the laser beam, and $L3$ lens focuses it to the focal plane. A is an aperture whose area is exactly twice that of the π area of the phase element.

types of masks, depending on the required spatial resolution of the selective evaporation. For relatively low resolutions we used a thin aluminum mask in contact with the substrate. The mask can be made either by lithographic techniques or by mechanical processing. The lateral resolution in this case is the thickness of the mask multiplied by the collimation angle of the atomic evaporation cloud. In our experiment we obtained resolutions of $\sim$10 μm for 100 μm mask thickness, indicating a collimation angle of $\sim$0.1 rad. Better collimation can be achieved by reducing the atomic source size, but at a cost of reduced evaporation flux. For very simple masks, such as a single circle, we also drilled a hole in a thick (2 mm) aluminum mask, but ensured a 45° drilling angle, which resulted in a very sharp edge ($<$10 μm). Evaporation through this mask yielded edges with a resolution of $\sim$1 μm. For submicron resolutions the mask must be formed lithographically on the substrate itself. We found that a 1 μm photoresist layer can serve as a protective layer for those areas where evaporation is unwanted. Removal of the photoresist in acid then removes also the dielectric layer that was evaporated over it in a standard ''lift-off'' process.

III. RESULTS

Figure 3 shows a surface profilometer trace for a section of the π phase element. The width of the slope of the surface in the figure is limited by the resolution of the profilometer. It was measured to be $\sim$1 μm with a calibrated optical microscope. The height of the evaporated surface profile is measured to be 680 nm, which fits the desired value within better than 1%. This was also the typical spread of our process over a period of several months.

We found that the depth errors were caused mainly by changes in the refractive index n of the evaporated layer. All the other possible error sources (stopping the evaporation not exactly at the fringe minima, errors in the monochromator and nonuniformity in the evaporated cloud) were usually much smaller. Note that according to Eqs. (1)–(3) a $+1\%$ error in n will cause a -1% error in depth and therefore a -1% $[+2.5\%]$ error in the phase for reflection (transmission) mode (for $n\sim1.38$), indicating smaller sensitivity to changes in n for the reflection mode. By selectively coating the dielectric layer on a flat reflective (e.g., metallic) surface a reflective phase element totally immune to errors in n can be obtained. This is due to the fact that the optical monitoring directly measures the phase difference caused by the deposited layer in reflection. For such an element the phased accuracy will be determined by the much smaller errors sources mentioned above and is expected be much better than 1%.

To demonstrate the validity of our proposed scheme we used it to fabricate a circular π binary phase plate for an argon laser. When such a plate is illuminated by a converging spherical wave whose area is twice that of the π phase area, exact destructive interference occurs at the focal region, resulting in a dark ellipsoid completely surrounded by light. We use that unusual light distribution as a ''dark'' optical trap for laser-cooled rubidium atoms.[8]

The π phase plate was characterizes by the optical setup of Fig. 4. A beam emerging from an argon laser was expended with a two-lens telescope, passed through the phase plate and an aperture, and focused with a third lens. The light distribution at the focal region was photographed with a charge coupled device (CCD) camera, and is shown in Fig. 5. The dark region in the center of the focal region is clearly seen, as are the surrounding light rings. Careful measurements with a scanning pinhole and a photodiode indicated that the residual light intensity at the center is $\sim$1000 times smaller than the intensity of the surrounding rings. This indicates that the destructive interference caused by the evaporated π phase mask was extremely accurate.

IV. DISCUSSION

To conclude, we proposed and demonstrated a new fabrication method for binary surface relief phase optical elements that is based on deposition of dielectric layers through

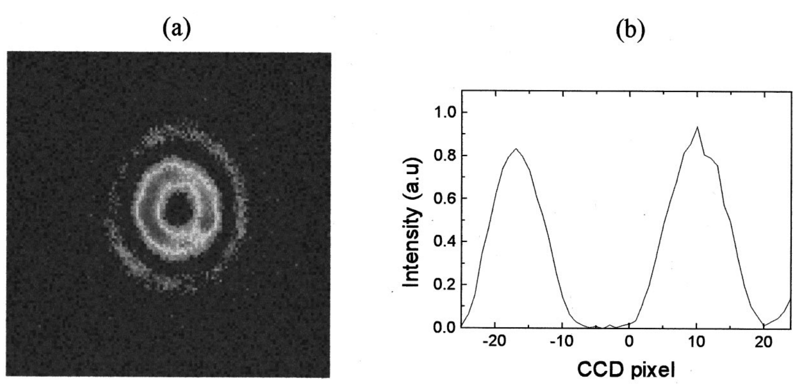

FIG. 5. Light intensity at the focal plane of the optical setup of Fig. 4 photographed with a CCD camera: (a) the CCD image at the focal plane, (b) a cross section of (a).

a space-variant contact mask in a commercial optical dielectric evaporator. *In situ* optical monitoring of the deposited layer thickness ensures good accuracy (~1%) and robustness of the process, and hence high (>99.9%) diffraction efficiencies. The method can have medium (a few micrometers) lateral resolution with contact metallic masks, or submicron resolution with a photoresist mask and a lift-off process. The method can be extended to multilevel binary surface relief elements[1] by repeating the evaporation process with several masks in exact analogy with multilevel binary etching techniques. It can also be extended to reflective elements adding a uniform reflective metallic layer either before or after the selective evaporation, yielding improved phase accuracy. Finally, transmission elements can be antireflection coated using the standard methods provided that the refractive index of the substrate and the evaporated level are very close.

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[6] High vacuum coating system BAK600, made by Balzers.
[7] We also tried to stop the evaporation at the middle of a reflection fringe, where the slope of the reflection plot is maximal, and therefore is also the expected sensitivity. However, being more sensitive to dc offsets it was found to be less reproducible than stopping the evaporation at the fringe minima.
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